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A THERMAL MODEL FOR ASPHALTIC CONCRETE

AFOSR GRANT 80-0234

Scientific Report
for the period Ending 31 December 1981

Prepared by

William H. Hightner
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INTRODUCTION

During calendar year 1981 the research effort of this grant was devoted primarily to three areas: (a) measurement of thermal properties of asphaltic concrete in the laboratory; (b) field tests performed to compare the results of the measured temporal and spatial temperature field induced in an asphaltic concrete pavement by a known energy input to those predicted by heat transfer theory using the thermal properties measured in the laboratory results; and, (c) a sensitivity analysis which indicated the influence of thermal properties of the asphalt and the heat source on the predicted temporal and spatial temperature field. Details of each of these tasks are given below and typical results are summarized.

LABORATORY MEASUREMENTS OF THERMAL PROPERTIES

A calorimeter used to measure the thermal conductivity and thermal diffusivity of asphaltic concrete was designed and constructed specifically for this research project. Because it is much easier to measure these properties if the heat flow through the specimen is one dimensional, it was important that the radial heat loss through the cylindrical specimen be minimal. To predict the radial heat loss for several candidate designs, a computer code was developed to solve the transient two dimensional heat transfer equation. It was found that using a 14.6 cm diameter sample about 2.5 cm thick, radial heat losses would be well within acceptable tolerances using the device shown schematically in Figure 1. (This device has a cooling base which is not shown in the Figure). Figure 2 shows the ratio of radial to axial heat loss for the device as a function of radial position in the sample. This Figure shown that the radial heat flow is essentially zero at the center of the sample and less than 1.5% of the axial (vertical) heat

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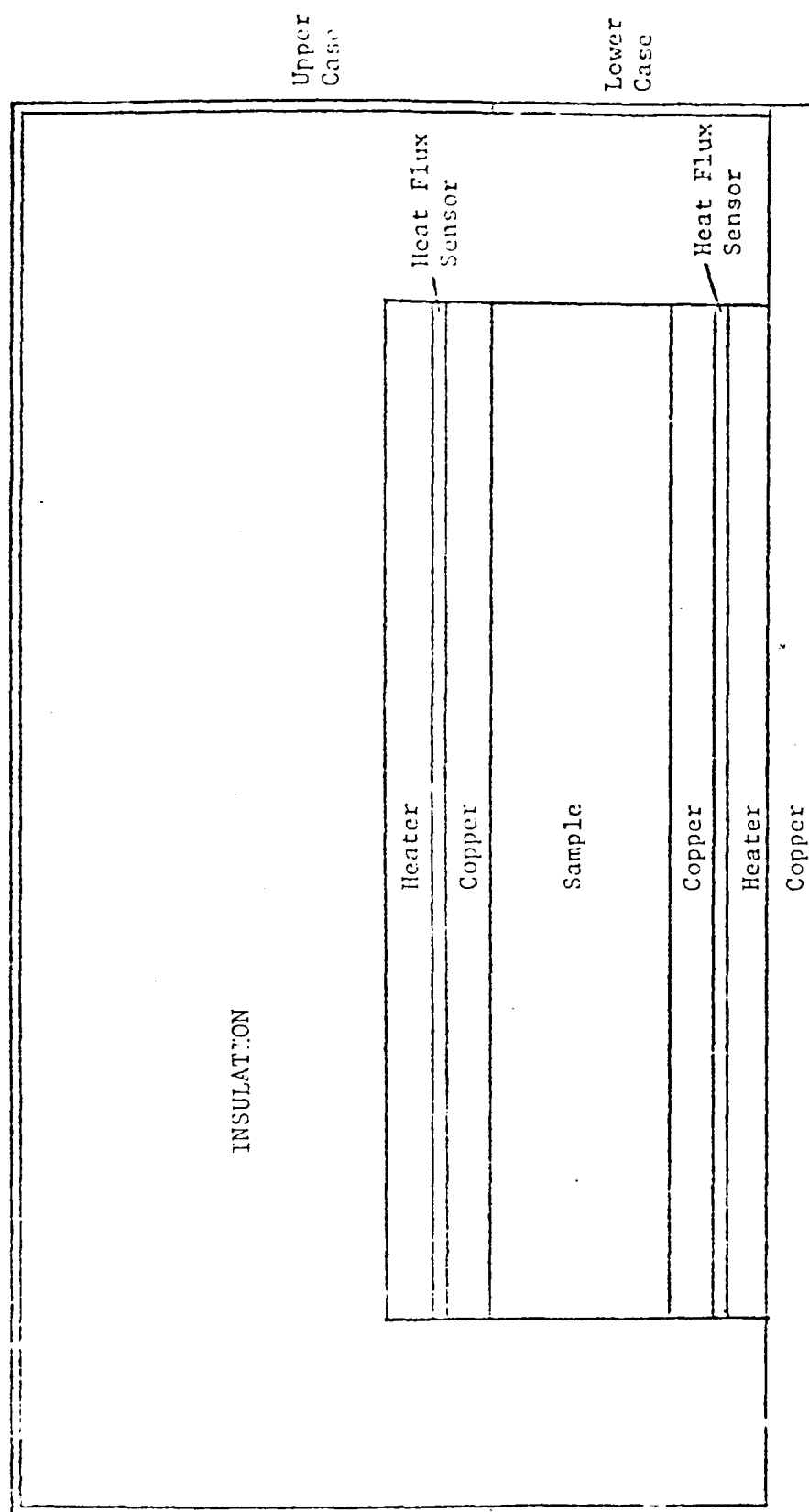


Figure 1. Modified Calorimeter

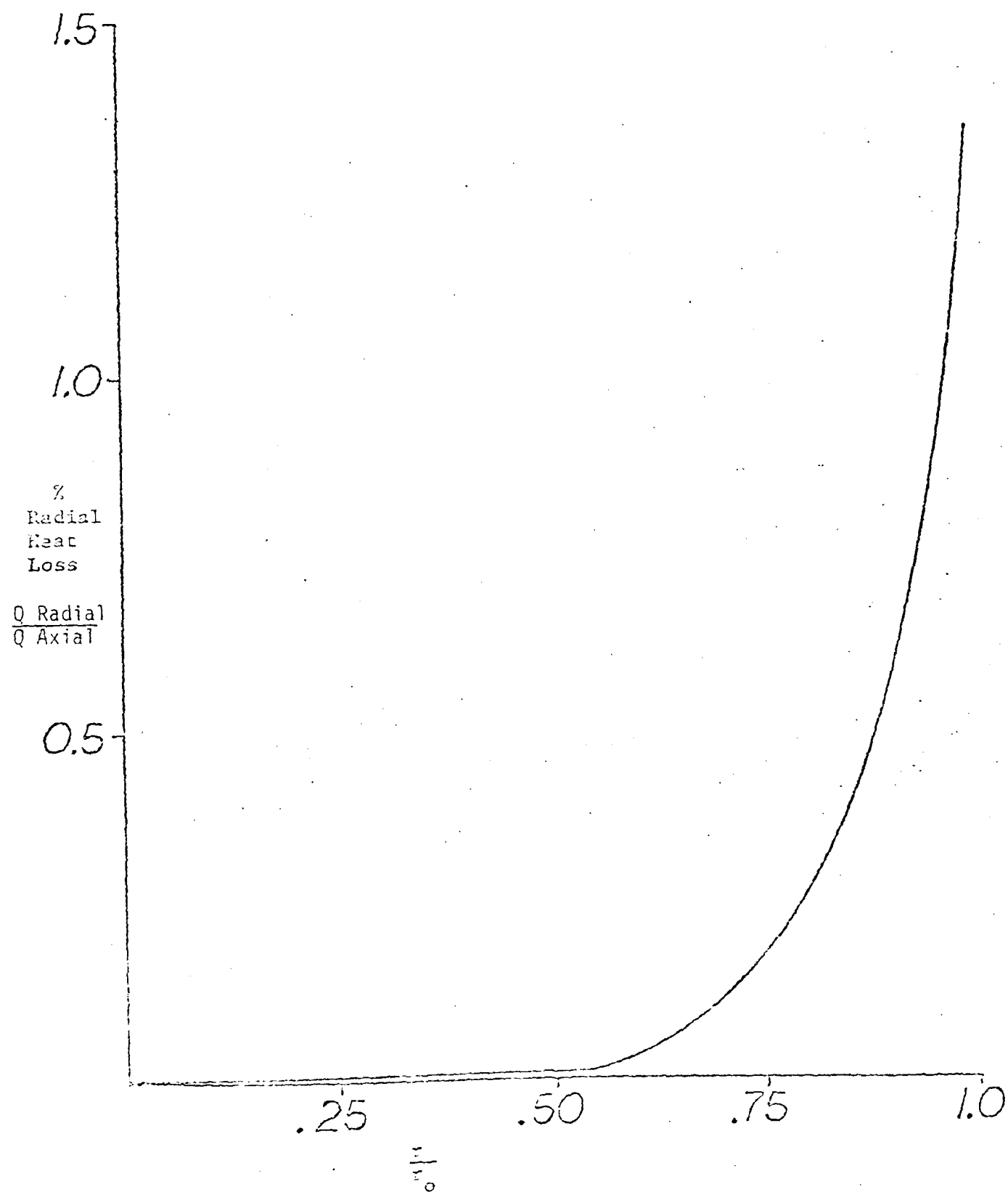


Figure 2 % Radial Heat Loss vs. Radial Position In
Modified Calorimeter Sample of Radius r_0

flow at the edges. In the laboratory experiments, fluxes were measured at $\frac{r}{r_0} = 0.2$ in the calorimeter where radial heat flow was less than 0.1% of the axial flow. These statistics are well within ASTM guidelines.

The heat flow through the sample in the calorimeter was assumed to be one dimensional thus making the analysis of the experiment much easier since all derivatives with respect to the radius r in the equation

$$\frac{1}{r} \frac{\partial}{\partial r} (k r \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) = \rho C_p \frac{\partial T}{\partial t} \quad (1)$$

vanish and thus

$$k \frac{\partial^2 T}{\partial z^2} = \rho C_p \frac{\partial T}{\partial t} \quad (2a)$$

or

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (2b)$$

In these equations, k is thermal conductivity, T is temperature, ρ is density, r and z are cylindrical coordinates, C_p is specific heat, α is thermal diffusivity ($\frac{k}{\rho C_p}$), and t is time.

To find the conductivity, k , a steady state condition is attained in the laboratory experiment so that derivatives with respect to t (time) vanish. Then, k can be determined from Equation (2a) by measuring the temperature gradient through the sample and the corresponding heat flux Q .

With k known, the calorimeter can also be used to find the diffusivity $\alpha (= \frac{k}{\rho C_p})$ if a transient test is run. The system is first brought to steady state and then the power to the upper heater (Figure 1) is increased. The resulting increased heat flux into the copper disk as well as the temperature of the disk are recorded as a function of time. By solving Equation (2b) the transient response to the heat flux boundary condition can be found. A computer code has been developed to solve the transient one dimensional energy equation using a finite difference technique. The computer code uses the measured heat flux as a boundary condition at the surface. The time scale of the test is short enough so

that the sample appears to be semi-infinite; thus the temperature of the lower face of the sample does not change during the test. An initial guess for α is made and the transient temperature response is calculated. If the calculated temperatures do not equal the measured temperatures, α is modified and another trial is run. This process is repeated until the final measured temperature is within 2% of the final calculated temperature.

The calorimeter was calibrated by measuring the thermal conductivity and diffusivity of a standard pure substance. In Table 1 below are the measured k values obtained at 3 different temperatures along with corresponding values cited in the literature for fused silica.

TABLE 1
CALIBRATION OF CALORIMETER-CONDUCTIVITY

$T(^{\circ}\text{C})$	Measured $k(\frac{\text{W}}{\text{m}^{\circ}\text{C}})$	Literature $k(\frac{\text{W}}{\text{m}^{\circ}\text{C}})$	% Error
25 ⁰	1.310	1.377	-4.9
60 ⁰	1.409	1.417	-0.6
85 ⁰	1.414	1.446	-2.2

The reliability of the calorimeter in measuring diffusivity can best be illustrated by Figure 3. The transient temperature response of fused silica is shown in the Figure along with the predicted response obtained using the known (literature) value of α in the one dimensional heat transfer code. As can be seen in Figure 3, the measured and predicted temperature-time response are very close.

With confidence in the results obtained on samples with known thermal properties in the calorimeter, tests were run to determine the thermal properties of asphaltic concrete. Samples were corer from the pavement, sliced, and inserted in the calorimeter and conductivity and diffusivity values were obtained using the procedures described above.

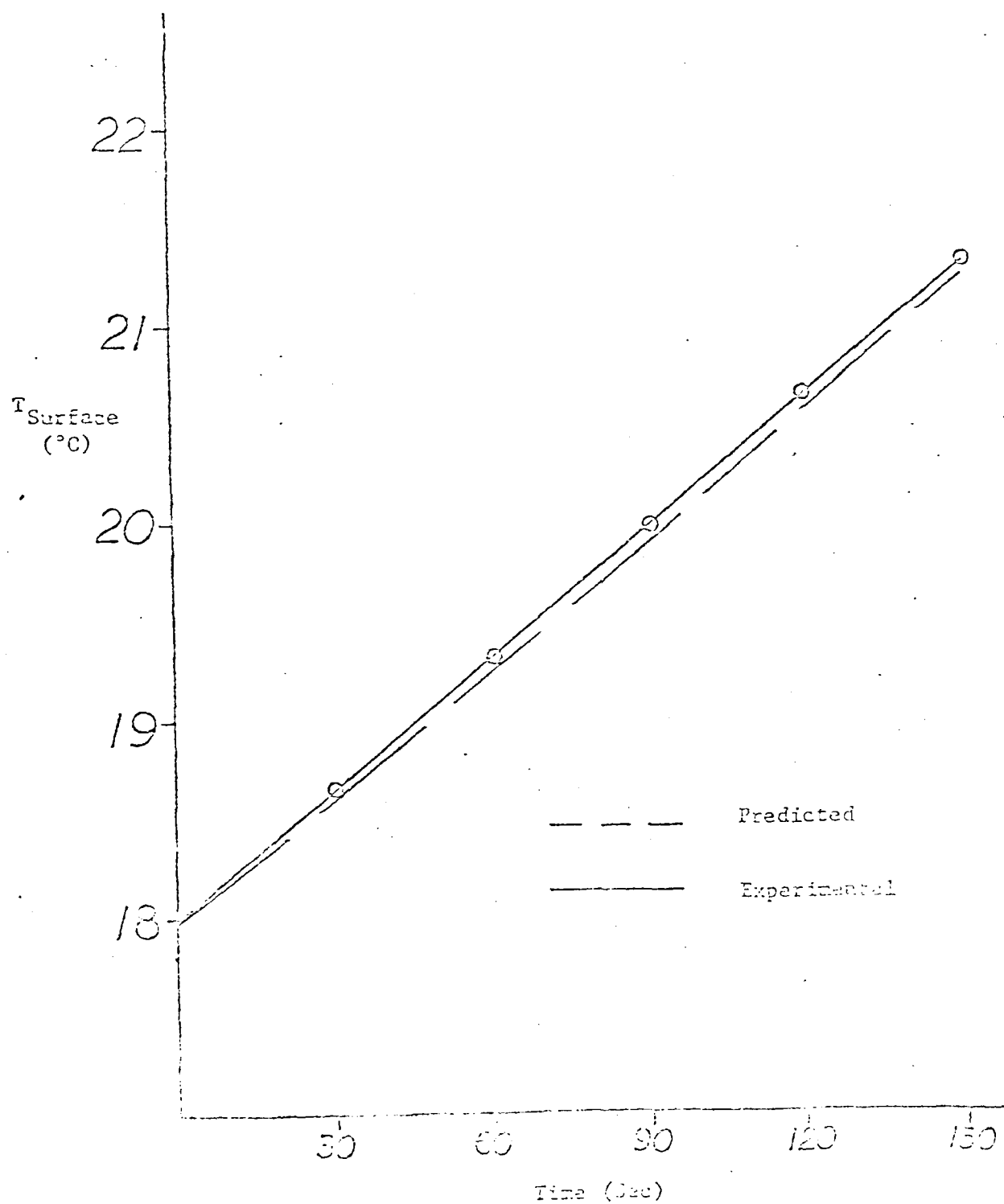


Figure 3 Calorimeter Diffusivity Test: Experimental vs. Predicted Temperature Response at Surface of Fused Silica Sample Using Known Value for α

FIELD TESTS

The objective of the field tests was to determine if the computer code could be used to predict the temporal-spatial temperature field of an in situ asphaltic concrete pavement of known thermal properties when subjected to a known thermal input. The thermal properties of the asphaltic concrete were determined as described above, but before the field tests could be carried out, thermal characteristics of the heat source had to be obtained.

A small portable propane heater was used as the heat source in the field tests. Heat is transferred to the pavement predominately by radiation and much less importantly by convection. Convection effects can be neglected with little loss of accuracy. The portable heater and the pavement can be modelled as two parallel plate and the heat transfer can be described as:

$$q = \frac{\sigma (T_H^4 - T_A^4)}{\frac{1}{\epsilon_H} + \frac{1}{\epsilon_A} - 1} \quad (3)$$

when T = temperature

ϵ = emissivity

σ = The Stefan-Boltzmann constant.

The subscripts H and A refer to the heater and asphalt surface, respectively.

The emissivity of asphalt varies little from a value of 0.9 (J. P. Holman, Heat Transfer, McGraw-Hill Book Co., 1972). Then the emissivity of the heater ϵ_H can be determined from Eq. 3 if the temperature and the heat flux, q , are measured. This was done in field experiments and ϵ_H was found to be 0.4 for T_H in the range of 410° to 550°C. This value is well within the range of that reported for steel (Holman, 1972) as it should be because, as seen from below, the heat source is seen mainly as sheet steel.

Now, with the thermal characteristics of the source heater known, and the thermal properties (k and α) at a particular point in a pavement determined in the lab as explained in the preceding section, field tests could be carried out

so that the measured temporal-spatial temperature field could be compared to that predicted by the one dimensional computer code.

Figure 4 shows typical comparison results for the temperature of the surface of asphalt when subjected to the heater at $T_H = 485^\circ\text{C}$ for 500 seconds at which time the heater was removed and the pavement surface was insulated. The agreement between predicted and observed surface temperatures was within 5°C for the duration of the test.

Figure 5 is a comparison of the measured and predicted temperature history at a depth of 3.2 cm below the pavement surface. The heater temperature, T_H , was 485°C and the heat source was removed and the surface insulated after 500 seconds. The difference between predicted and observed temperatures was within 7°C at all times.

SENSITIVITY ANALYSIS

The temporal-spatial temperature field in asphaltic concrete depends on 5 parameters (for a radiant heat source): the temperature of the heat source, T_H ; the emissivity of the heater, ϵ_H ; the emissivity of asphalt, ϵ_A ; the diffusivity of the asphaltic concrete, α , and; the conductivity of the asphaltic concrete, k . To determine the effect of each of these 5 variables on the temperature field, 4 of the variables were held constant while the 5th was varied from a nominal i.e. representative value. The temperature at the surface of the asphaltic concrete T_A was used as the dependent variable for purposes of illustration. The influence of T_H , ϵ_H and k are shown in Figures 6, 7, and 8, respectively.

The heater source temperature T_H has a large influence on T_A (Figure 6). This is because surface heat flux is mainly by radiation and is proportional to $(T_H^4 - T_A^4)$. The heat source temperature must be measured within about $\pm 1^\circ\text{C}$ to obtain a $\pm 5^\circ\text{C}$ accuracy in T_A .

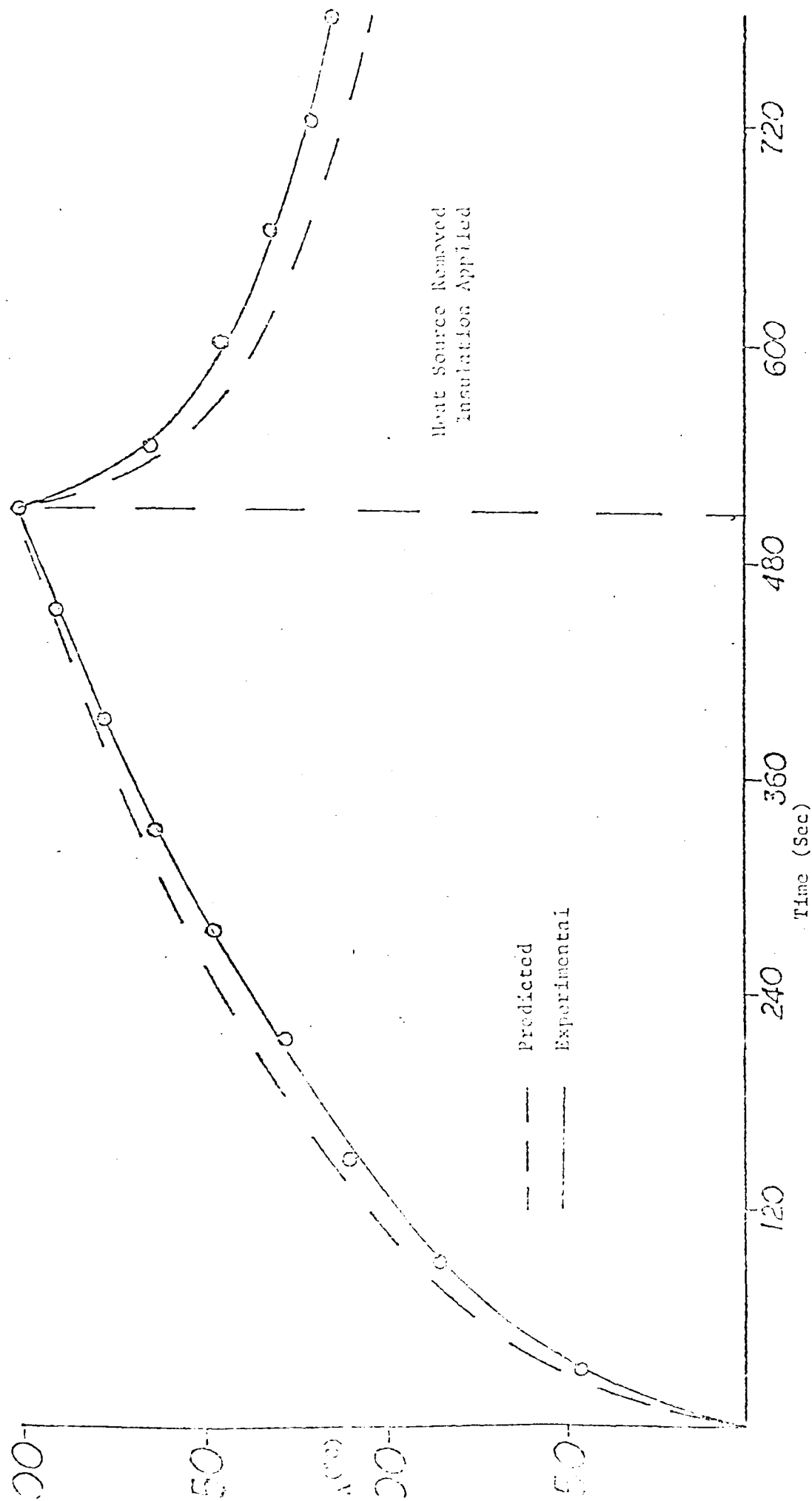


Figure 4 Experimental vs. Predicted Temperature Response at Surface
for $T_H = 485^\circ\text{C}$

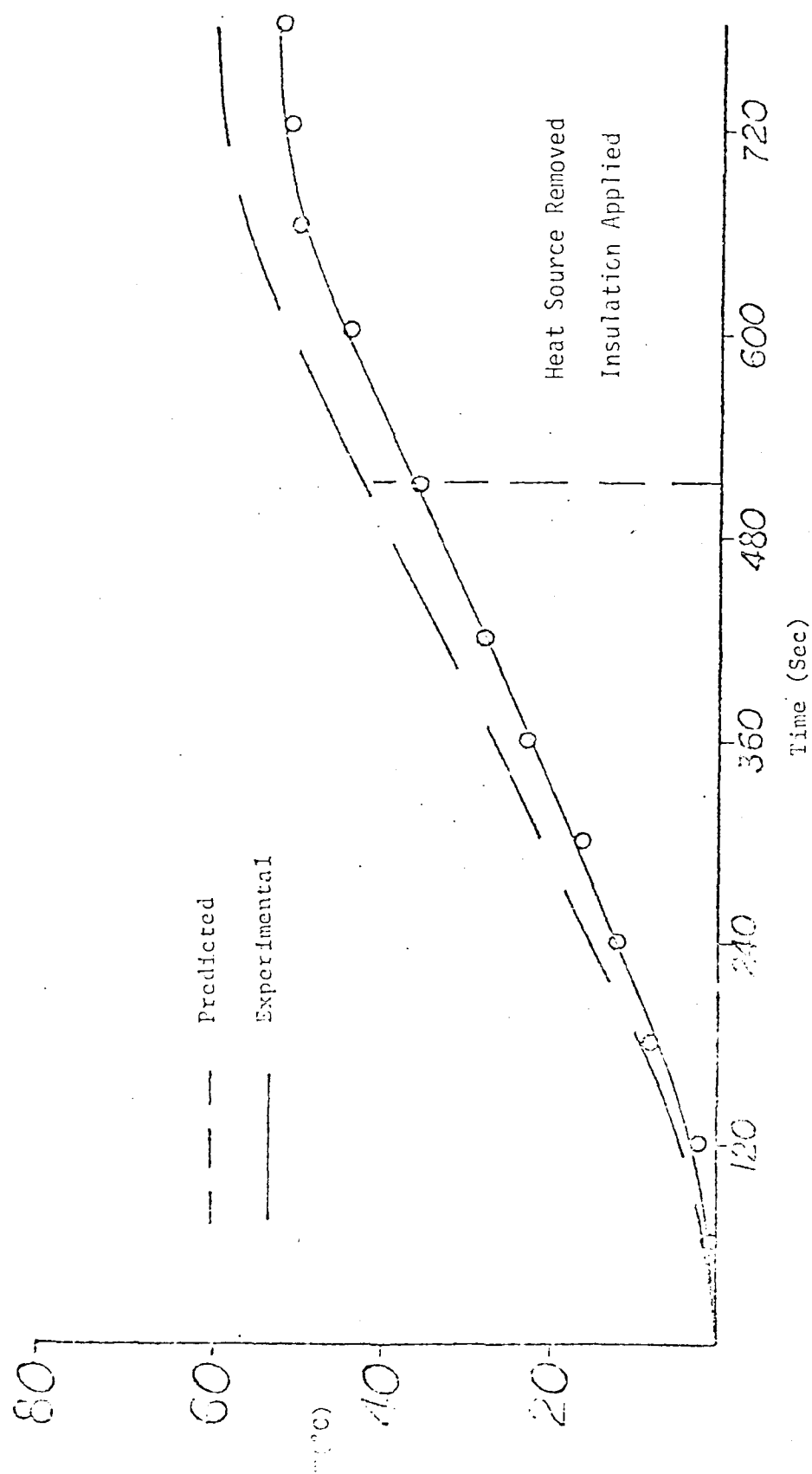


Figure 5 Experimental vs. Predicted Temperature Response
at Depth = 3.18 cm, $T_H = 485^\circ\text{C}$

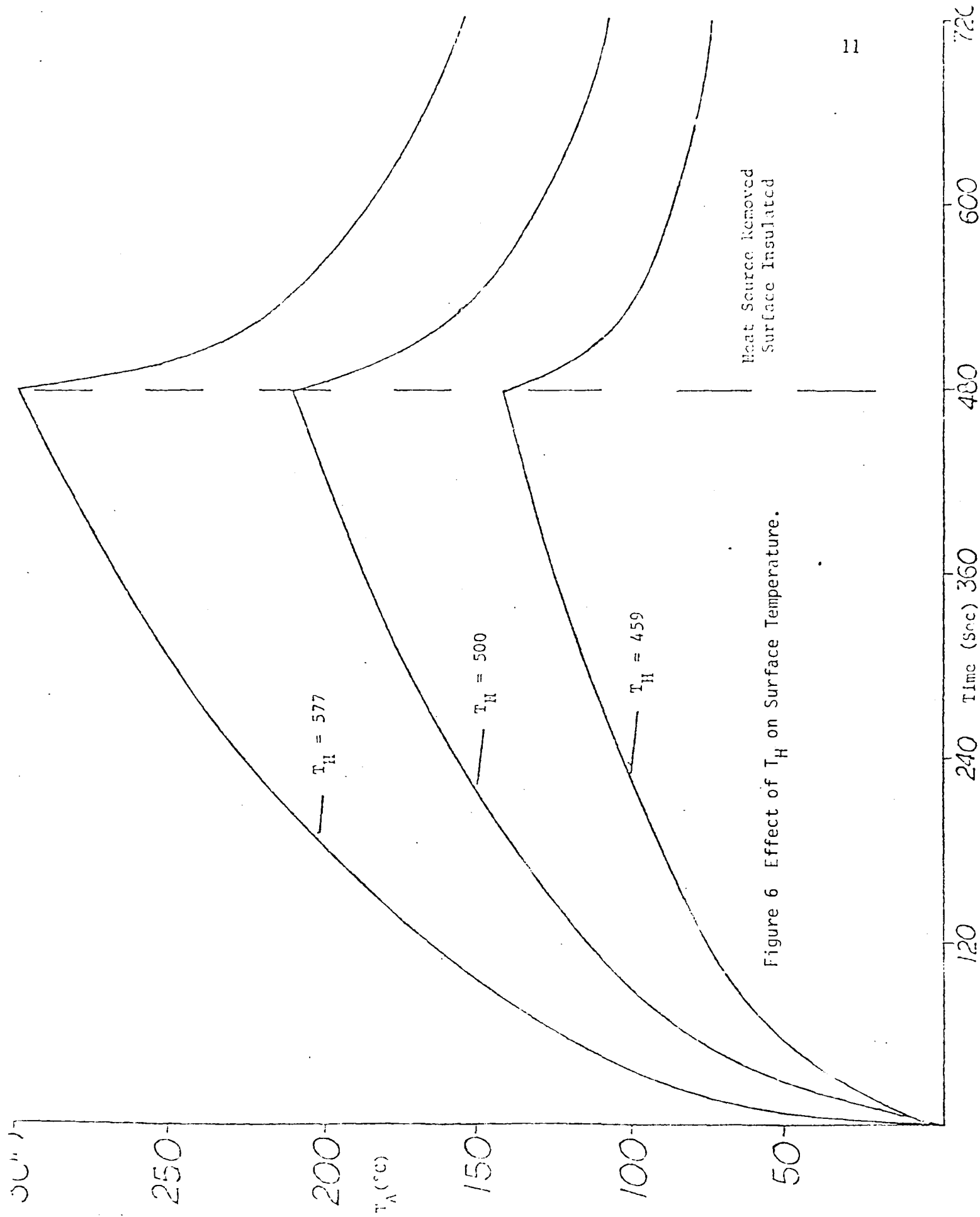


Figure 6 Effect of T_H on Surface Temperature.

Figure 7 shows that the change in surface temperature is almost directly proportional to a change in source emissivity ϵ_H . A $\pm 10\%$ variation in the source emissivity yields a $\pm 8\%$ change in T_A .

The effect of the conductivity, k , on the surface temperature is shown in Figure 8. The higher the value the faster the heat flow through the asphalt and thus the lower the surface temperature. After the heat source is removed, the higher the k the more rapidly the drop in T_A because the heat flows down through the asphalt faster. An increase in k by 10% causes a decrease in T_A of about 8.5% ; conversely, a decrease in k by 10% results in an increase in surface temperature of about 8.5% .

Sensitivity studies showed that the surface temperature T_A was rather insensitive to α , the diffusivity. The thermal diffusivity need only be measured to within $\pm 25\%$ to obtain a $\pm 5\%$ accuracy in predicting temperature response.

SUMMARY

A modified colorimeter has been developed to measure the thermal conductivity and thermal diffusivity of asphaltic concrete. Calibration of the calorimeter with a substance of known thermal properties (fused silica) indicated that the calorimeter performs well.

Thermal characteristics of a field heater were determined so that by determining the pavement thermal properties from lab tests the temporal-spatial temperature field of an asphaltic concrete pavement could be predicted. The results of a preliminary series of field tests were encouraging. The predicted and measured surface temperatures were very close while the predicted and measured temperatures with depth were generally within 10°C of one another.

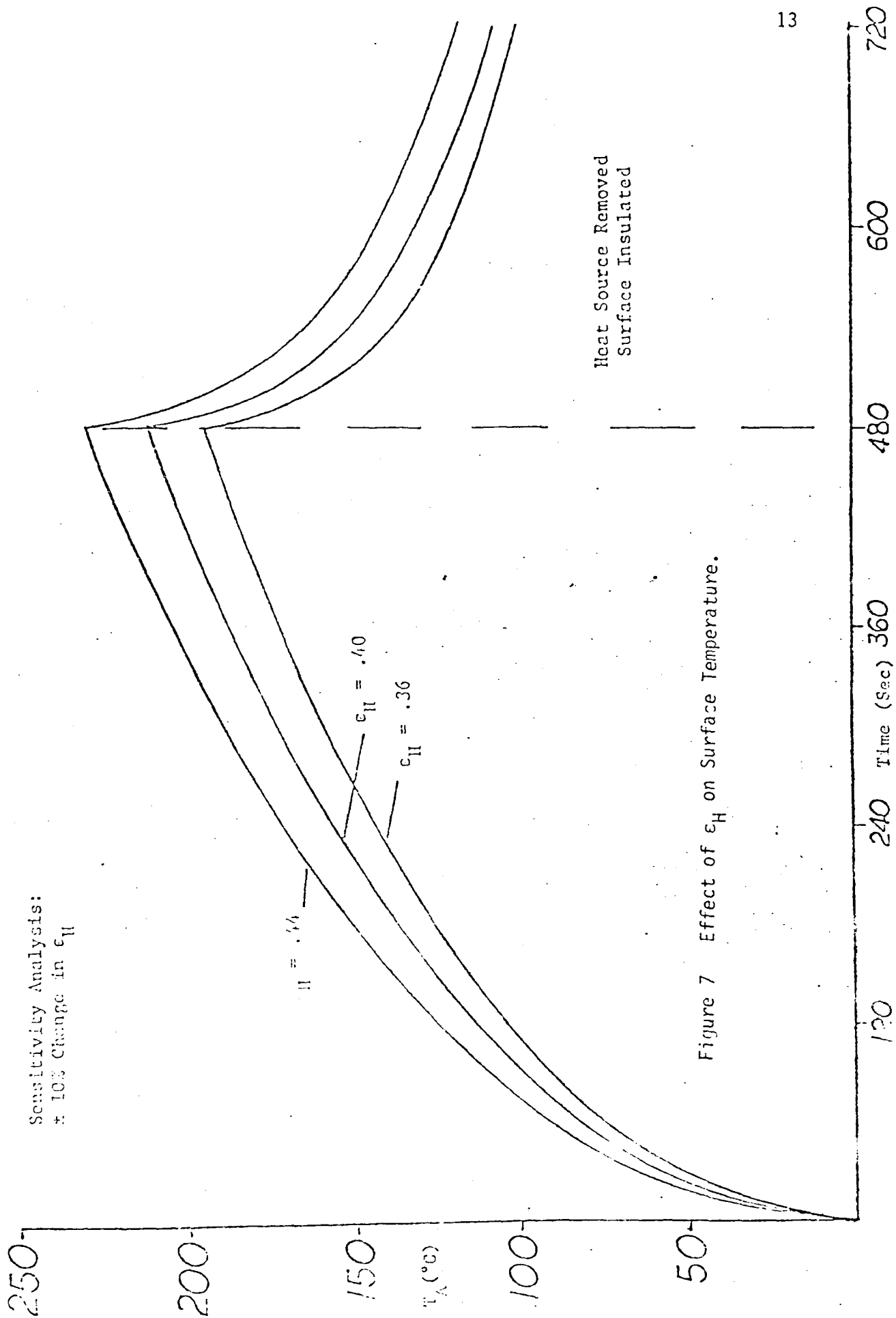


Figure 7 Effect of ϵ_H on Surface Temperature.

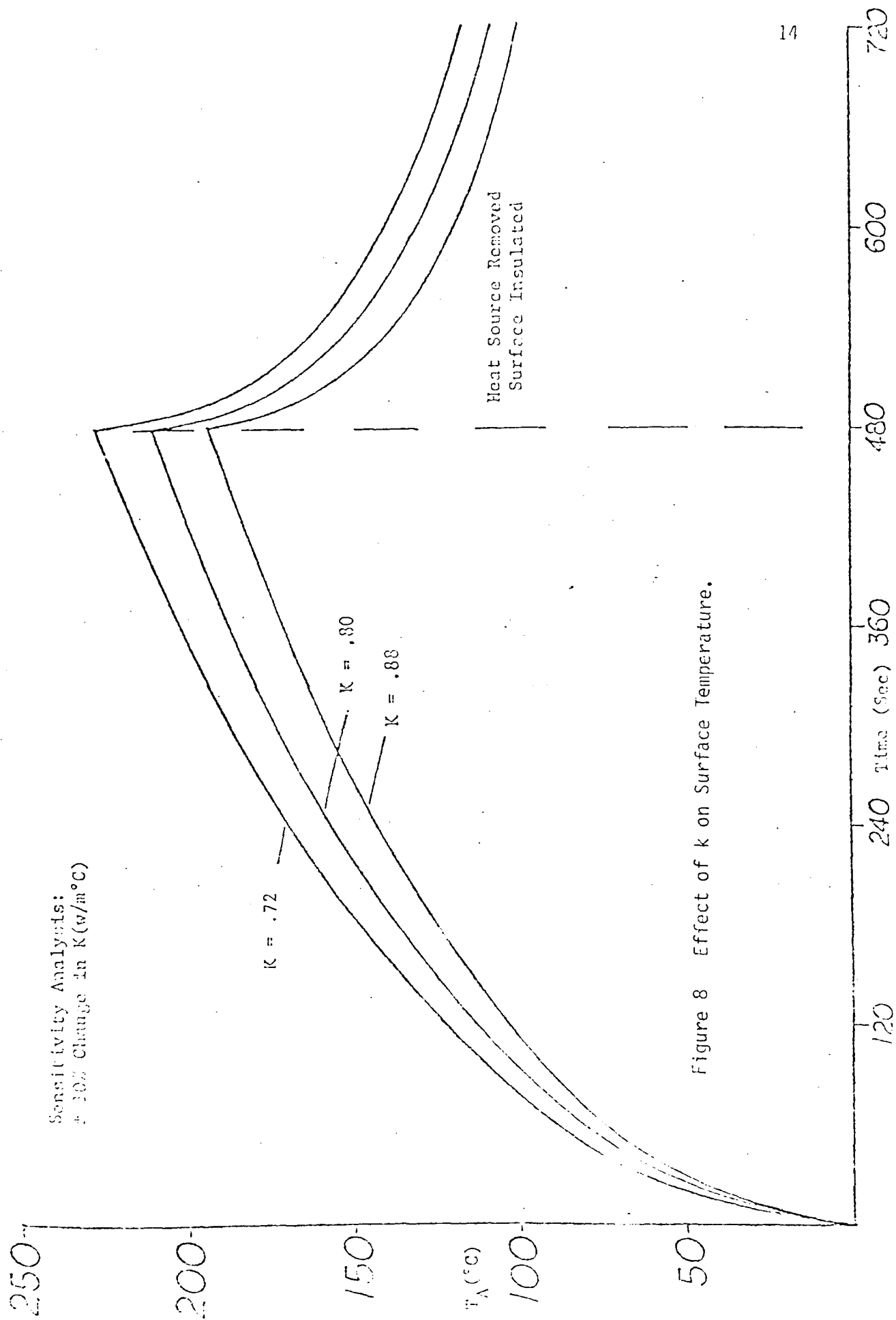


Figure 8 Effect of k on Surface Temperature.

A sensitivity analysis of the thermal parameters used in the one dimensional heat transfer computer code indicated that to predict the temporal-spatial temperature field with accuracy and confidence it is necessary to have precise values of the thermal conductivity and emissivity of asphaltic concrete and source temperature and emissivity of the (radiant) heater. The thermal diffusivity of the asphaltic concrete is not an important parameter.